CLAIMS

1. A photonic crystal waveguide including a core formed of a photonic crystal having periodicity in one direction which propagates electromagnetic wave in a direction perpendicular to the one direction, the photonic crystal being characterized in that:

the electromagnetic wave is propagated by a propagation mode of a photonic band present on a Brillouin zone boundary in a photonic band structure of the core; and

a side face of the core parallel to the one direction is in contact with a homogeneous medium cladding having a refractive index n_s, the side face satisfying the condition:

$$\lambda_0/n_s > a\lambda/(\lambda^2/4+a^2)^{0.5}$$

where λ_0 denotes wavelength of the electromagnetic wave in vacuum, a denotes the period of the photonic crystal, and λ denotes the period of the wave propagated through the core in a direction perpendicular to the one direction.

2. The photonic crystal waveguide according to claim 1, characterized in that a confinement cladding, which is formed of a homogeneous material or a photonic crystal having periodicity in at least the one direction, is arranged on a surface of the core perpendicular to the one direction to prevent electromagnetic wave propagated through the core from leaking out of the surface.

3. The photonic crystal waveguide according to claim 1 or 2, characterized in that the width 2L of the core in a direction perpendicular to the longitudinal direction of the waveguide is a range of:

$$s\lambda/2\cos\phi_0 \leq 2L < (s+1)\lambda/2\cos\phi_0$$

when the propagation angle ϕ of the electromagnetic wave satisfying:

$$\lambda_0/n_s - a(\lambda/\cos\phi)/\{(\lambda/2\cos\phi)^2+a^2\}^{0.5}=0$$

is in the range $0<\phi<90°$, the value in this range is defined as the maximum value ϕ_0 of propagation angles at which the electromagnetic wave is confined by the side face, and the phase shift amount is $s\pi$ when the wave propagated through the core is reflected by the side face at the maximum value ϕ_0 of the propagation angle, and s is in the range $0 \leq s \leq 1$.

4. The photonic crystal waveguide according to claim 1 or 2, characterized in that when the phase shift amount is $s\pi$ when the wave propagated through the core in a direction perpendicular to the one direction is perpendicularly incident on the side face and reflected thereby, s is in the range $0 \leq s \leq 1$, and the conditions:

$\lambda_0/n_s-2a>0$ and

$s\lambda/2 \leq 2L$

are satisfied.

5. The photonic crystal waveguide according to claim 4, characterized in that the width 2L of the core in a direction perpendicular to the longitudinal direction of the waveguide is in the range:

$s\lambda/2 \leq 2L<(s+1)\lambda/2$.

6. The photonic crystal waveguide according to any one of claims 1 to 5, characterized in that a confinement cladding layer, which is formed of a photonic crystal having periodicity in at least the one direction and formed of the same materials as the core, is arranged on a surface of the core, and a photonic bandgap formed by the cladding layer in the one direction confines the propagation mode in the one direction of the core, while making modes close to the propagation mode as radiation modes.

7. The photonic crystal waveguide according to any one of claims 1 to 6,

characterized by a phase modulating device on an end face of the core where the periodic structure thereof is exposed, the phase modulating device coupling the wave propagated through the core to an external plane wave.

8. The photonic crystal waveguide according to claim 7, characterized in that when n denotes a refractive index of an external medium and λ_0 denotes a wavelength of an external plane wave in vacuum, the phase modulating device uses the end face of the core parallel to the one direction as an external coupling face, and couples, in the coupling face, plane waves having an incident angle θ in the one direction that is represented by the formula:

$$n \cdot \sin\theta \cdot (a/\lambda_0) = 0.5$$

to the end face.

9. The photonic crystal waveguide according to claim 7, characterized in that, when n denotes a refractive index of an external medium and λ_0 denotes a wavelength of an external plane wave in vacuum, the phase modulating device uses the end face of the core parallel to the one direction as an external coupling face, and, in the coupling face, causes two plane waves having the same phase and having incident angles $\pm\theta$ in the one direction that is represented by the formula:

$$n \cdot \sin\theta \cdot (a/\lambda_0) = 0.5$$

to interfere with each other to couple them to the end face.

10. The photonic crystal waveguide according to claim 7, characterized in that:

the phase modulating device is a phase grating arranged close to, in contact with, or integrally with an incident surface, which is an end face of the core parallel to the one direction, and has a period in the same direction as the photonic crystal forming the core that is twice the period of the photonic crystal; and

the phase grating couples the external plane wave to the wave propagated

through the core.

11. The photonic crystal waveguide according to claim 7, characterized in that the phase modulating device is a phase grating arranged close to, in contact with, or integrally with an end face of the core parallel to the one direction, and has the same period in the same direction as the photonic crystal forming the core; and

the incident angle or exit angle θ of external plane wave coupled to the wave (propagated light) propagated through the core by the phase grating satisfies the formula:

$n \cdot \sin\theta \cdot (a/\lambda_0)=0.5$

where n denotes a refractive index of an external medium, and λ_0 denotes wavelength of the external plane wave in vacuum.

12. The photonic crystal waveguide according to claim 7, characterized in that the phase modulating device is a phase grating arranged close to, in contact with, or integrally with an end face of the core parallel to the one direction, and has a period in the same direction as the photonic crystal forming the core that is twice the period of the photonic crystal; and

the incident angle or exit angle θ of external plane wave coupled to the wave (propagated light) propagated through the core by the phase grating satisfies the formula:

$n \cdot \sin\theta \cdot (a/\lambda_0) = 0.5$

where n denotes a refractive index of an external medium, and λ_0 denotes wavelength of the external plane wave in a vacuum.

13. The photonic crystal waveguide according to claim 7, characterized in that the phase modulating device directly couples the external plane wave to a slant end face of the core that is inclined with respect to the one direction.

14. The photonic crystal waveguide according to claim 13, characterized in that a prism or mirror is arranged in contact with or close to the slant end face of the core to change the incoming direction or outgoing direction of the external plane wave.

15. The photonic crystal waveguide according to claim 14, characterized in that the incoming direction or outgoing direction of the external plane wave is matched with the propagation direction in the core formed by the photonic crystal.

16. The photonic crystal waveguide according to claim 14, characterized in that the incoming direction or outgoing direction of the external plane wave is perpendicular to the propagation direction in the core formed by the photonic crystal.

17. The photonic crystal waveguide according to claim 14, characterized in that the prism has a refractive index of 3 or more.

18. The photonic crystal waveguide according to claim 14, characterized by a slant end face of the core, which is inclined with respect to the one direction, and a diffraction grating that is arranged close to, in contact with, or integrally with the slant end face.

19. The photonic crystal waveguide according to claim 18, characterized in that the incoming direction or outgoing direction of the external plane wave coupled to the wave propagated through the core by the diffraction grating is matched with the propagation direction in the core formed of the photonic crystal.

20. The photonic crystal waveguide according to any one of claims 1 to 19, characterized in that the width of the core in a direction perpendicular to the longitudinal direction of the waveguide is varied in a tapered manner.

21. A photonic crystal waveguide including a core formed of a photonic crystal having periodicity in one direction which propagates electromagnetic wave in a direction perpendicular to the one direction, the photonic crystal characterized in that:

the electromagnetic wave is propagated by a propagation mode of a high-order photonic band exists on the Brillouin zone center line in the photonic band structure of the core; and

a side face of the core parallel to the one direction is in contact with a homogeneous medium cladding having refractive index n_s, the side face satisfying the condition:

$$\lambda_0/n_s-\lambda>0$$

where λ_0 denotes wavelength of the electromagnetic wave in vacuum, a denotes the period of the photonic crystal, and λ denotes the period of the wave propagated through the core in a direction perpendicular to the one direction.

22. The photonic crystal waveguide according to claim 21, characterized in that a confinement cladding, which is formed of a homogeneous material or a photonic crystal having periodicity in the at least one direction, is arranged on a surface of the core perpendicular to the one direction for preventing the electromagnetic wave propagated through the core from leaking out of the surface.

23. The photonic crystal waveguide according to claim 21 or 22, characterized in that the width 2L of the core in a direction perpendicular to the longitudinal direction of the waveguide is in a range of:

$$s\lambda/2\cos\phi_0\leq 2L<(s+1)\lambda/2\cos\phi_0$$

with the propagation angle ϕ of the electromagnetic wave satisfying:

$$\lambda_0/n_s-\lambda/\cos\phi=0$$

and being in a range of $0<\phi<90°$, with a value in this range being defined as a maximum value ϕ_0 of propagation angles at which the electromagnetic wave is

confined by the side face; and

the phase shift amount is $s\pi$ when the wave propagated through the core is reflected by the side face at the maximum value ϕ_0 of the propagation angle, and s being in the range $0 \leq s \leq 1$.

24. The photonic crystal waveguide according to any one of claims 21 to 23, characterized in that a confinement cladding layer, which is formed of a photonic crystal having periodicity in at least the one direction and is formed of the same materials as the core, is arranged on a surface of the core, and a photonic bandgap formed by the cladding layer confines the propagation mode in the one direction of the core, while making the modes close to the propagation mode as a radiation modes.

25. The photonic crystal waveguide according to any one of claims 21 to 24, characterized by:

a phase modulating device on an end face of the core where the periodic structure thereof is exposed, the phase modulating device coupling the wave propagated through the core to the external plane wave.

26. The photonic crystal waveguide according to claim 25, characterized in that when n denotes a refractive index of an external medium and λ_0 denotes a wavelength of the external plane wave in vacuum, the phase modulating device uses the end face of the core parallel to the one direction as an external coupling face, and, in the coupling face, causes two plane waves having the same phase and having an incident angle $\pm\theta$ in the one direction that is represented by the formula:

$$n \cdot \sin\theta \cdot (a/\lambda_0) = 1.0$$

to interfere with each other to couple them to the end face.

27. The photonic crystal waveguide according to claim 25, characterized in that when n denotes a refractive index of an external medium, and λ_0 denotes a

wavelength of the external plane wave in vacuum, the phase modulating device uses the end face of the core parallel to the one direction as an external coupling face, and, in the coupling face, causes two plane waves having the same phase and having an incident angle $\pm\theta$ in the one direction that is represented by the formula:

$$n \cdot \sin\theta \cdot (a/\lambda_0)=1.0$$

and the plane wave with $\theta=0$ to interfere simultaneously to couple them to the end face.

28. The photonic crystal waveguide according to claim 25, characterized in that:

the phase modulating device is a phase grating arranged close to, in contact with, or integrally with an incident surface, which is an end face of the core parallel to the one direction, and has the same period in the same direction as the photonic crystal forming the core; and

the phase grating couples the external plane wave to the wave propagated through the core.

29. The photonic crystal waveguide according to any one of claims 21 to 28, characterized in that the width of the core in a direction perpendicular to the longitudinal direction of the waveguide is varied in a tapered manner.

30. A homogeneous medium waveguide including a core formed of a homogeneous medium having a refractive index n_0 and a limited thickness in one direction which propagates the electromagnetic wave in a direction perpendicular to the one direction, the homogeneous medium waveguide being characterized in that:

the electromagnetic wave is propagated by a first-order or higher-order propagation mode in the one direction of the core; and

a side face of the core parallel to the one direction is in contact with a homogeneous medium cladding having refractive index n_s, the side face satisfying the

condition:

$n_s < n_0$.

31. The homogeneous medium waveguide according to claim 30, characterized in that a confinement cladding, which is formed of a homogeneous material or a photonic crystal having periodicity in at least the one direction, is arranged on a surface of the core perpendicular to the one direction to prevent electromagnetic wave propagated through the core from leaking out of the surface.

32. The homogeneous medium waveguide according to claim 30 or 31, characterized in that the width 2L of the core in the longitudinal direction of the waveguide is in a range of:

$s\lambda_0\cos\psi/2\sin\phi_0 \leq 2L < (s+1)\lambda_0\cos\psi/2\sin\phi_0$

with the propagation angle ϕ of the electromagnetic wave satisfying:

$n_s - n_0\{\sin^2\psi + \cos^2\psi\cos^2\phi\}^{0.5} = 0$

and being in a range of $0 < \phi < 90°$, the value in this range is defined as a maximum value ϕ_0 of propagation angles at which the electromagnetic wave is confined by the side face, and the phase shift amount is $s\pi$ when the wave propagated through the core is reflected by the side face at the maximum value ϕ_0 of the propagation angle, and s being in a range of $0 \leq s \leq 1$.

33. The homogeneous medium waveguide according to claim 30 or 31, characterized in that when the phase shift amount is $s\pi$ and the wave propagated through the core in a direction (XZ plane direction) perpendicular to the one direction is perpendicularly incident on the side face and reflected thereby, s is in a range of $0 \leq s \leq 1$, and the conditions:

$n_s - n_0\sin\psi < 0$ and

$s\lambda_0\cos\psi/2 \leq 2L$

are satisfied.

34. The homogeneous medium waveguide according to claim 33, characterized in that the width 2L of the core is in a range of:

$s\lambda_0\cos\psi/2 \leq 2L<(s+1)\lambda_0\cos\psi/2$.

35. The homogeneous medium waveguide according to any one of claims 30 to 34, characterized in that the external plane wave having an incident angle θ in the one direction is represented by the formula:

$\sin\theta=(n_0/n_m)\sin\psi$

where n_0 denotes a refractive index of the core, n_m denotes a refractive index of the incident light side, and ψ denotes a propagation angle of high-order mode light propagated through the core, is coupled to an end face of the core parallel to the one direction so that the external plane wave is used as incident light or outgoing light.

36. The homogeneous medium waveguide according to any one of claims 30 to 34, characterized in that the external plane wave is coupled to a slant end face of the core that is inclined with respect to the one direction, and the external plane wave has an incident angle for coupling to the high-order mode of the propagation angle ψ in the one direction, so that the external plane wave is used as incident light or outgoing light.

37. The homogeneous medium waveguide according to any one of claims 30 to 34, characterized in that a prism or mirror is arranged in contact with or close to the slant end face of the core that is inclined with respect to the one direction to couple high-order mode light in the one direction propagated through the core to the external plane wave so that the external plane wave is used as incident light or outgoing light.

38. The homogeneous medium waveguide according to claim 37,

characterized in that the incoming direction or outgoing direction of the external plane wave is matched with the propagation direction in the waveguide.

39. The homogeneous medium waveguide according to claim 37, characterized in that the incoming direction or outgoing direction of the external plane wave is perpendicular to the propagation direction in the waveguide.

40. The homogeneous medium waveguide according to claim 37, characterized in that the prism has a refractive index of 3 or more.

41. The homogeneous medium waveguide according to any one of claims 30 to 34, characterized in that a diffraction grating is arranged close to, in contact with, or integrally with the slant end face of the core that is inclined with respect to the one direction.

42. The homogeneous medium waveguide according to claim 41, characterized in that the incoming direction or outgoing direction of the external plane wave is matched with the propagation direction in the waveguide.

43. The homogeneous medium waveguide according to any one of claims 30 to 34, characterized in that a phase grating is provided close to, in contact with, or integrally with an end face of the core that is parallel to the one direction, and diffraction light of the external plane wave by the phase grating is coupled to high-order mode light propagated through the core in the one direction, so that the plane wave is used as incident light or outgoing light.

44. The homogeneous medium waveguide according to any one of claims 30 to 43, characterized in that the width of the core in a direction perpendicular to the longitudinal direction of the waveguide is varied in a tapered manner.

45. An optical device for use as a directional coupler, the optical device including two waveguides formed to be bent close to each other in a coupling region having a predetermined coupling length, the optical device being characterized in that:

each of the two waveguides is formed by the photonic crystal waveguide according to any one of claims 1 to 29 or the homogeneous medium waveguide according to any one of claims 30 to 44.

46. An optical device for use as a Mach Zehnder optical switch, the optical device including a single linear waveguide, two waveguides branched from the waveguide, and a single linear waveguide formed by merging the two waveguides, the optical device being characterized in that:

each of the waveguides is formed by the photonic crystal waveguide according to any one of claims 1 to 29 or the homogeneous medium waveguide according to any one of claims 30 to 44.

47. An optical device for use as an optical delay line, the optical device including a linear waveguide and a single waveguide, which has a delay portion, the optical device being characterized in that:

the waveguide and the delay portion are formed by the photonic crystal waveguide according to any one of claims 1 to 29 or the homogeneous medium waveguide according to any one of claims 30 to 44.

48. An optical device for use as a dispersion control device, the optical device including a waveguide formed by the photonic crystal waveguide according to any one of claims 1 to 29 or the homogeneous medium waveguide according to any one of claims 30 to 44, the optical device being characterized in that:

propagation having a large dispersion is used as propagated light propagated through the waveguide.

49. An optical device being characterized by:

a waveguide formed by the photonic crystal waveguide according to any one of claims 1 to 29 or the homogeneous medium waveguide according to any one of claims 30 to 44, the core containing a material having nonlinear characteristics; and

two electrodes arranged on two surfaces of the waveguide in the one direction.

50. An optical device being characterized by:

a waveguide formed by the photonic crystal waveguide according to any one of claims 1 to 29 or the homogeneous medium waveguide according to any one of claims 30 to 44, the core containing a material having nonlinear characteristics;

two electrodes arranged on two surfaces of the waveguide in the one direction; and

a modulator for changing voltage or electric current applied to the two electrodes.

51. An optical device being characterized by:

the photonic crystal waveguide according to any one of claims 1 to 29 or the homogeneous medium waveguide according to any one of claims 30 to 44, wherein confinement of the cladding is made imperfect to generate refracted light from the core.